

# **DRAFT**

## **CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY AIR RESOURCES BOARD**

### **TECHNICAL SUPPORT DOCUMENT FOR STAFF PROPOSAL REGARDING REDUCTION OF GREENHOUSE GAS EMISSIONS FROM MOTOR VEHICLES**

## **CLIMATE CHANGE OVERVIEW**



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## Introduction

The earth's climate is changing because human activities are altering the chemical composition of the atmosphere through the buildup of GHGs, primarily carbon dioxide (CO<sub>2</sub>), methane, nitrous oxide, and hydrofluorocarbons. Climate research scientists are also suggesting that climate change in recent decades may have been mainly caused by non-CO<sub>2</sub> GHGs, particularly tropospheric ozone, methane, hydrofluorocarbons, and black carbon particles. The heat-trapping property of the GHGs is undisputed. Although there is uncertainty about exactly how and when the earth's climate will respond to enhanced concentrations of GHGs, observations indicate that detectable changes are under way. There most likely are and will continue to be changes in temperature and precipitation, soil moisture, and sea level, all of which could have significant adverse effects on many ecological systems, as well as on human health and the economy.

### A. Climate Change Overview

Climate change is a shift in the "average weather" that a given region experiences. This is measured by changes in the features we associate with weather, such as temperature, wind patterns, precipitation, and storms. Global climate change means change in the climate of the Earth as a whole. Global climate change can occur naturally; an ice age is an example of naturally occurring climate change. The Earth's natural climate has always been, and still is, constantly changing. The climate change we are seeing today, however, differs from previous climate change in both its rate and its magnitude.

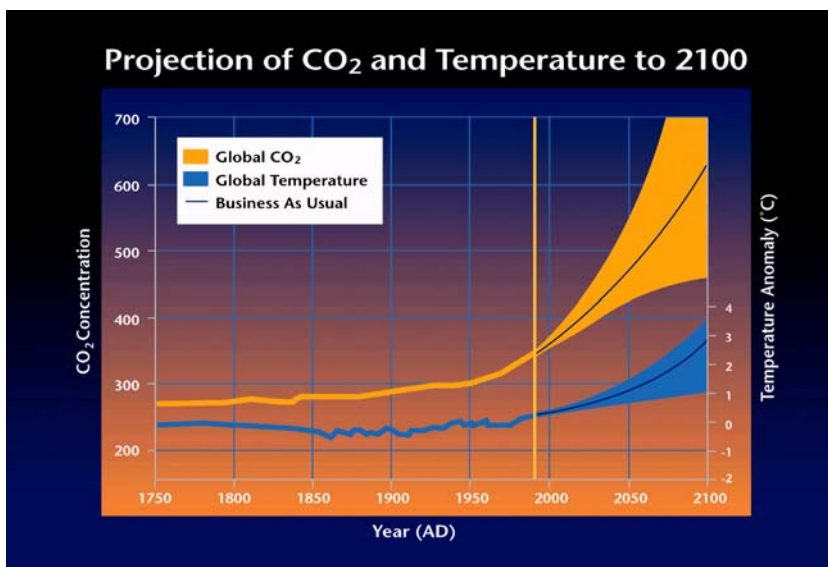
The temperature on Earth is regulated by a system known as the "greenhouse effect". Naturally occurring GHGs, primarily water vapor, carbon dioxide, methane, and nitrous oxide absorb heat radiated from the Earth's surface. As the atmosphere warms, it in turn radiates heat back to the surface, to create what is commonly called the "greenhouse effect". Without the effect of these naturally occurring gases, the average temperature on the Earth would be -18 °C (-0.4 °F), instead of the current average of 15 °C (59 °F). Life as we know it would be impossible.

Human activities are exerting a major and growing influence on some of the key factors that govern climate by changing the composition of the atmosphere and by modifying the land surface. The human impact on these factors is clear. The concentration of CO<sub>2</sub> in the atmosphere has risen about 30 percent since the late 1800s (NAST, 2001). This increase has resulted from the burning of coal, oil, and natural gas, and the destruction of forests around the world to provide space for agriculture and other human activities. Rising concentrations of CO<sub>2</sub> and other GHGs are intensifying Earth's natural greenhouse effect. Global projections of population growth and assumptions about energy use indicate that the CO<sub>2</sub> concentration will continue to rise, likely reaching between two and three times its late-19th-century level by 2100 (Figure 1, Source: NAST, 2001).

The Third Assessment Report of the International Panel on Climate Change (IPCC, 2001) and the National Research Council of the National Academies (NRC, 2001) conclude that the global climate is changing at a rate unmatched in the past one thousand years. The IPCC Assessment cites new and stronger evidence that most of the global warming observed over the last fifty years is attributable to human activities

and that anthropogenic climate change will persist for many centuries. However, while the NRC Report generally agrees with the IPCC Assessment, it does not rule out that some significant part of these changes is also a reflection of natural variability. The observed changes over the last fifty years and those projected for the future include higher maximum air temperatures, more hot days, fewer cold days, greater extremes of drying and heavy rainfall, and sea level rise (IPCC, 2001).

Many sources of data indicate that the Earth is warming faster than at any time in the previous 1,000 years. The global mean surface temperature has increased by 1.1 °F since the 19th century (IPCC, 2001). The 10 warmest years of the last century all occurred within the last 15 years. For example, 2002 and 2003 are tied as the second warmest years on record, according to a year-end review of climate data by the National Oceanic and Atmospheric Administration. Satellite data indicate that 2003 was the fourth warmest year for temperatures centered in the middle troposphere at altitudes from two to six miles. The average temperature in the lower troposphere (surface to about five miles) was the third warmest since satellite measurements began in 1979. The NAST (2001) report indicates that the warming in the 21st century will be significantly larger than in the 20th century. Scenarios examined in this Assessment, which assume no major interventions to reduce continued growth of world GHG emissions, indicate that temperatures in the US will rise by about 5-9°F (3-5°C) on average in the next 100 years, which is more than the projected *global* increase. This rise is very likely to be associated with more extreme precipitation and faster evaporation of water, leading to greater frequency of both very wet and very dry conditions. Warming or cooling of the earth will impact water supplies, energy supply and demand, agriculture, forestry, natural habitat, outdoor recreation, air quality, and public health. As a result, global climate change issues are receiving increasing national and international attention from governments, business and industry, the research community, environmental interests, and the public (IPCC, 2001).



**Figure 1.** Projection of carbon dioxide and temperature to 2100 (Source: NAST, 2001). Note: Temperature anomaly is the projected changes in temperature due to anthropogenic effects.

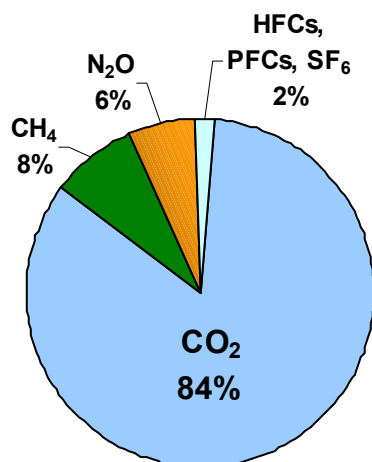
### B. Climate Change Pollutants

Naturally occurring GHGs include water vapor, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and ozone (O<sub>3</sub>). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also GHGs, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are substances which deplete stratospheric ozone, they are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The United Nations Framework Convention on Climate Change (UNFCCC) defers to this earlier international treaty; consequently these gases are not included in national GHG inventories. Some other fluorine containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>)—do not deplete stratospheric ozone but are potent GHGs. These latter substances are addressed by the UNFCCC and accounted for in State and national GHG inventories.

In September 2000, the California Legislature passed Senate Bill 1771 (SB1771, 2000), requiring the California Energy Commission (CEC), in consultation with other state agencies, to update California's inventory of GHG emissions in January 2002 and every five years thereafter. The CEC (2002) report includes emissions of six GHGs: CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, and SF<sub>6</sub>. Although the first three gases are also emitted from natural sources, this report primarily focuses on emissions due to human activities (anthropogenic emissions). The report also concluded that there were major uncertainties associated with input data quality, protocols available to disaggregate data, and inventory methodologies applied to the State. It was recommended that future GHG inventories could be improved by: (1) incorporating improved data and methods; (2) updating emissions estimates to the most recent year; and, (3) presenting a

discussion of the uncertainty in emissions estimates from key sources. A brief discussion of each of these GHGs is given below. Individual climate change species are briefly discussed in the following section. Detailed discussions of GHG emissions and sinks are given in the CEC (2002) report.

**Carbon Dioxide (CO<sub>2</sub>):** Carbon is naturally cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. In the atmosphere, carbon generally exists in its oxidized form, as CO<sub>2</sub>. Increased CO<sub>2</sub> concentrations in the atmosphere have been primarily linked to increased combustion of fossil fuels. Figure 2 shows the distribution of California's emissions by GHG type. At 84 percent of the total, CO<sub>2</sub> is the largest single contributor to emissions from in-state sources.



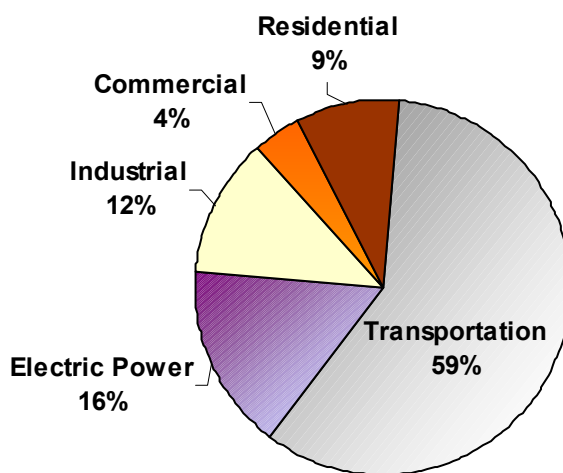
**Figure 2.** Distribution of California greenhouse gas emissions by gas in 1999, expressed in terms of CO<sub>2</sub> equivalent (adapted from CEC, 2002).

Fossil fuel combustion accounted for 98 percent of gross California CO<sub>2</sub> emissions. Other sources of CO<sub>2</sub> emissions in California include non-energy production processes and waste combustion. Carbon sinks in California brought about by land-use change and forestry practices offset roughly 5 percent of gross State CO<sub>2</sub> emissions.

California's total CO<sub>2</sub> emissions from fossil fuel combustion in 1999 were 356 million metric tons of CO<sub>2</sub> equivalent (MMTCO<sub>2</sub> Eq), which accounts for approximately 7 percent of the U.S. emissions from this source. The transportation sector accounted for the largest portion of emissions, averaging 59 percent of the total CO<sub>2</sub> emissions from fossil fuel combustion in California for the period 1990-1999. Within the transportation sector, gasoline consumption accounted for the greatest portion of emissions.

In-state power plants contribute about 16 percent of the CO<sub>2</sub> emissions from the combustion of fossil fuels. California imports a substantial amount of electricity from out-of-state power plants. If carbon dioxide emissions from out-of-state power plants serving California were included, emissions would increase by about 5.5 million metric tons and the rate of increase of gross greenhouse gas emissions in the 1990 to 1999 period

would have been about four percent. These emissions are not included for California in compliance with international and national protocols (CEC, 2002). Figure 3 presents the contribution of each sector to CO<sub>2</sub> emissions from fossil fuel combustion in 1999.



**Figure 3.** Carbon Dioxide Emissions from the Combustion of Fossil Fuels by Sector for 1999 (adapted from CEC, 2002).

The CEC (2002) report indicates that CO<sub>2</sub> emissions from fossil fuel combustion tracked economic and population growth in the early 1970s. Emissions remained flat through 1986, and then started to grow through the end of the decade. Economic and population growth both outpaced the growth in emissions during this period.

**Methane (CH<sub>4</sub>):** Methane accounted for more than 7 percent of gross 1999 GHG emissions in California, in terms of equivalent CO<sub>2</sub> emissions. Methane is produced during anaerobic decomposition of organic matter in biological systems. Decomposition occurring in landfills accounts for the majority of anthropogenic CH<sub>4</sub> emissions in California and in the United States as a whole. Agricultural processes such as enteric fermentation, manure management, and rice cultivation are also significant sources of CH<sub>4</sub> in California.

While it is well established that exhaust from vehicles using hydrocarbon fuels contains CH<sub>4</sub>, there are few published data concerning the magnitude of CH<sub>4</sub> emissions from the modern, and likely future, vehicle fleet. Metz (2001) concluded that the anthropogenic contribution of road transport to the global CH<sub>4</sub> budget is less than 0.5 percent. Three-way catalyst emission control systems installed on all modern vehicles are effective in removing CH<sub>4</sub> from vehicle exhaust (Nam et al., 2004). It seems highly likely that the future will bring increasingly stringent regulations concerning the effectiveness and durability of vehicle emission control systems. Hence, it is likely that emissions of CH<sub>4</sub> from gasoline- and diesel-powered vehicles will be reduced from their already low values. A possible exception to this trend would be the increased use of compressed natural gas (CNG) powered vehicles. However, based on the emission measurements reported in Nam et al., (2004) even assuming a substantial fraction of CNG-powered vehicles, the tailpipe CH<sub>4</sub> emissions from such vehicles are likely to have negligible environmental impact. While refueling losses would be another source of CH<sub>4</sub> emissions

from CNG vehicles, safety considerations would mandate effective controls of such emissions. It seems reasonable to conclude that the environmental impact of CH<sub>4</sub> emissions from vehicles is negligible and is likely to remain so for the foreseeable future.

**Nitrous Oxide (N<sub>2</sub>O):** Nitrous oxide emissions accounted for nearly 6 percent of GHG emissions (CO<sub>2</sub> equivalent) in California in 1999. The primary sources of anthropogenic N<sub>2</sub>O emissions in California are agricultural soil management and fossil fuel combustion in mobile sources. Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. Both mobile and stationary combustion emit N<sub>2</sub>O, and the quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, some types of catalytic converters installed to reduce motor vehicle pollution can promote the formation of N<sub>2</sub>O. U.S. EPA (2003) estimates suggest that, in 2001, N<sub>2</sub>O emissions from mobile combustion were 13 percent of U.S. N<sub>2</sub>O emissions, while stationary combustion accounted for 3 percent. From 1990 to 2001, combined N<sub>2</sub>O emissions from stationary and mobile combustion increased by 9 percent, primarily due to increased rates of N<sub>2</sub>O generation from on road vehicles.

Behrentz et al., (2004) conducted a pilot study to measure exhaust emissions of N<sub>2</sub>O in order to gain information concerning the important variables in catalyst and driving conditions that most affect N<sub>2</sub>O emission from motor vehicles. Their results indicate that the average N<sub>2</sub>O emissions factor for the 37 vehicles tested was 20 ± 4 mg/km, significantly lower than previous reports of average values of ~35 mg/km (Dasch, 1992; Ballantyne et al., 1994; Barton and Simpson, 1994; Michaels et al., 1998). The difference between the previously reported emission factors and those presented in this pilot study could be related to the introduction of new technologies on some of the vehicles tested since they play a significant role in the amount of N<sub>2</sub>O emitted by the vehicles. The differences between this pilot study and those reported previously could also be related to difference in the vehicle fleets studied. This issue will be resolved with ARB's future analysis of a much larger database of N<sub>2</sub>O emissions. However, It is generally expected N<sub>2</sub>O emission from light-duty vehicles will continue this pattern of decreasing emissions with increasingly stringent NO<sub>x</sub> control technologies.

**Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>):** HFCs are primarily used as substitutes for ozone-depleting substances (ODS) regulated under the Montreal Protocol. PFCs and SF<sub>6</sub> are generally emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. There is no aluminum or magnesium production in California; however, the rapid growth in the semiconductor industry leads to greater use of PFCs.

For vehicular HFC emissions, four emission sources, all related to air conditioning, should be considered: emissions leaking from the hoses, seals and system components of vehicle air conditioning system, and emissions that are released when the air conditioning system is opened for servicing. HFC emissions can also occur when the vehicle is scrapped at the end of its useful life or due to sudden releases (e.g., traffic accident refrigerant releases). R-134a, also known as HFC-134a is presently the vehicle refrigerant of choice among vehicle manufacturers. The assessment of mobile air



conditioning system technology and associated cost analysis are included in later chapter.

**Other Radiatively Important Gases:** In addition, there are a number of man-made pollutants, emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), that have indirect effects on terrestrial or solar radiation absorption by influencing the formation or destruction of other GHGs. These include carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide. These compounds, regulated in the United States and California pursuant to the Clean Air Act, are often referred to as “criteria pollutants.” The criteria pollutants are reactive compounds, and they tend to remain in the atmosphere for a much shorter time than previously discussed gases. As shown in Table 1, CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, and HFC-134a have atmospheric lifetimes ranging from a century to ten years. Reactive compounds typically last only hours or days. The sequence of reactions that removes CO, NO<sub>x</sub>, and NMVOCs from the atmosphere, however, tends to promote the formation of ozone. Ozone in the stratosphere protects life on Earth from ultraviolet radiation, but ozone at ground level causes respiratory distress in people and animals and, also, is a potent (though short-lived) GHG. The lifetime of criteria pollutants in the atmosphere varies from weeks to months, which imparts an element of uncertainty in estimating tropospheric ozone radiative forcing effects.

It is generally difficult to make an accurate determination of the contribution of ozone precursors to global warming. The reactions that produce ozone are strongly affected by the relative concentrations of various pollutants, the ambient temperature, and local weather conditions.

Molecular hydrogen (H<sub>2</sub>) is a trace component of the lower atmosphere. Hydrogen is not radiatively-active and therefore does not have a direct impact on climate; however, it has an indirect impact on climate change as (a) it is involved in the production of tropospheric ozone, and (b) it can modify the concentration of methane through its affect on the concentration of the hydroxyl radical.

Since the 1980s, alternative options for fulfilling the global energy demand have been developed. The widespread use of H<sub>2</sub> produced with renewable energy sources currently appears to be a promising option, in particular for non-stationary energy uses. Although H<sub>2</sub> fuel cells themselves are a “clean” technology, producing water vapor (a GHG) as exhaust, emissions of GHGs and ozone precursors associated with the production of H<sub>2</sub> must be considered (Schultz et al., 2003). Furthermore, the release of molecular hydrogen may increase because of leakage attributable to the production, transport, storage, and end use of H<sub>2</sub> (Zittel and Altmann, 1996). At present, the average leak rate to be expected in a full-scale hydrogen-driven economy is very uncertain (Schultz et al., 2003).

Sulfur dioxide, on the other hand, probably exerts a net cooling effect on the climate. Sulfur dioxide is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds that are effective in promoting cloud formation. The clouds, in turn, reflect sunlight back into space, cooling the planet. Sulfur dioxide emissions are regulated in the United States and California under the Clean Air Act, and their concentrations have declined

considerably in recent years. This is due to low-sulfur fuels for mobile and stationary sources. California primarily depends on clean-burning natural gas rather than coal or oil, which typically have higher sulfur content, to meet its energy needs.

**Aerosols:** Aerosols are extremely small particles or liquid droplets found in the atmosphere. Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulfates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous aerosols (e.g., black carbon or organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning. Aerosols affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds.

Recent modeling and field studies indicate that aerosol light absorption by black carbon particles is an important component of climate forcing (Jacobson, 2001; Chung and Seinfeld, 2002; Hansen and Nazarenko, 2003,). The global mean radiative forcing of aerosol light absorption may be comparable to that of GHGs. Radiative forcing is often specified as the net change in energy flux in the atmosphere, and is expressed in watts per square meter ( $W/m^2$ ) (heat per area of the Earth's surface). Black carbon (BC) is a strong absorber of solar radiation; however, particles containing BC in the atmosphere both scatter and absorb solar radiation. Because BC-containing particles prevent radiation from reaching the Earth's surface, they act to cool the surface, but because they absorb radiation, they warm the atmosphere itself. Previous work has also shown that the overall radiative effect of aerosol BC depends significantly on the manner in which the BC is mixed with non-absorbing aerosols such as sulfate. While the atmospheric warming effect of BC and its surface cooling are well established, the resulting climate forcing from BC has not been clearly established.

Unlike GHGs that exhibit comparatively homogeneous global concentrations, aerosols are very heterogeneously dispersed, and thus the influence of aerosols is stronger regionally than globally. Observations from the Indian Ocean Experiment (Krishnan and Ramanathan, 2002) showed that aerosol-induced changes in regional radiative fluxes can be an order of magnitude larger than the global mean forcing by aerosols or GHGs. Altered regional stability by atmospheric heating by light-absorbing aerosol alters larger scale circulation and the hydrological cycle, enough so as to account for observed temperature and precipitation changes in China and India, according to a climate modeling study (Menon et al., 2003).

The reduction of NMVOC,  $NO_x$ ,  $SO_2$ , and particulate matter (PM) emissions remains a desirable goal for many reasons. To achieve health-based air quality standards, the ARB's programs primarily focus on reducing levels of criteria pollutants, such as ozone and its precursors, carbon monoxide, and inhalable PM as well as reducing emissions of air toxics. California's unique emissions and fuel standards for cars, trucks, buses, motorcycles, and other motor vehicles have dramatically reduced criteria pollutant emissions, as have controls on non-automotive pollution sources that are administered by the State's 35 local air pollution control districts. California has achieved these improvements despite the State's substantial growth in population, vehicle use, and business activities.

Understanding the role of aerosols in climate change requires inclusion of realistic representations of aerosols and their radiative forcings in climate models. However, compared to GHGs with long atmospheric residence times, the optical properties and temporal and spatial patterns of aerosols are poorly understood. Uncertainty in aerosol radiative forcing arises because neither emission factors, which determine atmospheric concentrations, nor optical properties are fully known. The IPCC (2001) and the NACIP (2002) have identified radiative forcing due to aerosols, and in particular light absorbing aerosols, as one of the most uncertain components of climate change models. For a more extensive review of aerosol particle impacts on climate change, the reader is referred to Attachment A of this report.

### C. Global Warming Potentials: General concept of climate change and definition

The term “radiative forcing” has been employed in the IPCC (2001) assessment to denote an externally imposed perturbation in the radiative energy budget of the Earth’s climate system. Radiative forcing of the surface-troposphere system, resulting, for example, from a change in GHG concentrations, is the change in the balance between radiation coming into the atmosphere and radiation going out. A positive radiative forcing tends, on average, to warm the surface of the Earth, and negative forcing tends, on average, to cool the surface.

The impact of GHG emissions upon the atmosphere is related not only to radiative properties, but also to the length of time the GHG remains in the atmosphere. Radiative properties control the absorption of radiation per kilogram of gas present at any instant, but the lifetime of the gas controls how long an emitted kilogram remains in the atmosphere and hence its cumulative impact on the atmosphere’s thermal budget. The climate system responds to changes in the thermal budget on time-scales ranging from the order of months to millennia depending upon processes within the atmosphere, ocean, and biosphere.

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a GHG. Indirect radiative forcing occurs when chemical transformations of the original gas produce other GHGs, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the Earth (e.g., affect cloud formation). The concept of a Global Warming Potential (GWP) has been developed to compare the ability of each GHG to trap heat in the atmosphere relative to another gas. Carbon dioxide (CO<sub>2</sub>) was chosen as the reference gas to be consistent with IPCC guidelines. GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). While any time period can be selected, the 100 year GWPs are recommended by the IPCC and will be employed by the ARB for policy making and reporting purposes.

GWP values allow a comparison of the impacts of emissions and reductions of different gases. According to the IPCC (2001), GWPs typically have an uncertainty of  $\pm 35$  percent. In addition to communicating GHG emissions in units of mass, we have also chosen to use GWPs to reflect their inventories in carbon dioxide-equivalent terms because it places all of the GHGs on the same comparative scale. Table 1 lists GWPs

for CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFC-134a, for the 20, 100, and 500 years time frames. It should be noted that when the lifetime of the species in question differs substantially from the response time of CO<sub>2</sub> (nominally about 150 years), then the GWP becomes very sensitive to the choice of time horizon. Thus, the GWP concept is only relevant for compounds that have sufficiently long lifetimes to become globally well-mixed. Therefore, short-lived gases and aerosols with vertical or horizontal variations pose a serious problem in the simple GWP framework.

**Table 1.** Numerical estimates of global warming potentials compared with carbon dioxide (kilograms of gas per kilogram of carbon dioxide -- adapted from IPCC 2001).

Climate Pollutants	Lifetime (years)	Global Warming Potential		
		20 years	100 years	500 years
CO <sub>2</sub>	~150	1	1	1
CH <sub>4</sub>	12	62	23	7
N <sub>2</sub> O	114	275	296	156
HFC-134a	~14	3,300	1,300	400

As mentioned earlier, some gases can indirectly affect radiative forcing, mainly through chemical processes. For example, tropospheric O<sub>3</sub> provides a significant radiative forcing of the climate system, but its production occurs indirectly, as a result of atmospheric chemistry following emissions of precursors such as NO<sub>x</sub>, CO, and NMHCs. Indirect effects will be described below for a number of key gases.

**Carbon monoxide:** CO is produced when carbon-containing fuels undergo incomplete combustion. As indicated in the IPCC third assessment report (2001), CO does not absorb terrestrial infrared strongly enough to be counted as a direct GHG. However, it has an indirect radiative forcing effect by elevating concentrations of CH<sub>4</sub> and tropospheric O<sub>3</sub> through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical or OH) that would otherwise assist in destroying CH<sub>4</sub> and tropospheric O<sub>3</sub>. It has been proposed that CO emissions should have a GWP because of its effects on the lifetimes of other GHGs (Prather, 1996; Daniel and Solomon, 1998).

The emission of CO perturbs OH, which in turn can then lead to an increase in the CH<sub>4</sub> lifetime. This term involves the same processes whereby CH<sub>4</sub> itself influences its own lifetime and hence GWP value (Prather, 1996) and is subject to similar uncertainty. Emissions of CO can also lead to the production of O<sub>3</sub>, with the magnitude of O<sub>3</sub> formation dependent on the amount of NO<sub>x</sub> present. As with CH<sub>4</sub>, this effect is quite difficult to quantify due to the highly variable and uncertain NO<sub>x</sub> distribution (Emmons et al., 1997). Table 2 presents estimates of the CO GWP due to O<sub>3</sub> production and to feedbacks on the CH<sub>4</sub> cycle from two-dimensional model studies along with the box-model estimate for the latter term alone from Daniel and Solomon (1998). Table 2 shows that the 100-year GWP for CO is likely to be 1.0 to 3.0, while that for shorter time horizons is estimated at 2.8 to 10. These estimates are subject to large uncertainties, as discussed further in the IPCC report (2001).

Because of the difficulty in accurately calculating the amount of O<sub>3</sub> produced by CO emissions, an accurate estimate of the entire indirect forcing of CO requires a three-dimensional chemical model. Wild et al (2001) have developed a method for analyzing the response of concentrations of O<sub>3</sub> and CH<sub>4</sub> to changes in the quantity of air pollutant emissions, using a three-dimensional global chemical transport model (CTM) that combines a global climate model with a photochemical reaction model. The results demonstrated that although the production of O<sub>3</sub> is suppressed when only NO<sub>x</sub> emissions are reduced, the concentration of CH<sub>4</sub> rises, thereby possibly accelerating global warming in the long-term. When NO<sub>x</sub> and CO emissions are reduced simultaneously, however, it has been shown that the build up of methane is abated and that this approach is thus effective in mitigating global warming. They also discussed some clear inadequacies in their modeling results. For example, the treatment of urban emissions in the CTM does not include the effects of non-linearities in small-scale plumes where NO<sub>x</sub> concentrations may be sufficiently high to suppress O<sub>3</sub> production or to remove NO<sub>x</sub> rapidly. It is not clear in these cases that the OH effect is also proportionally suppressed. Uncertainties such as these can be evaluated by comparing the global CTM with carefully designed high-resolution regional models.

**Table 2.** Estimated indirect Global Warming Potentials for CO for time horizons of 20, 100, and 500 years (adapted from IPCC third assessment report (2001)).

	Indirect Global Warming Potentials Time horizon		
	20 years	100 years	500 years
Daniel and Solomon (1998): box model considering CH <sub>4</sub> feedbacks only	2.8	1.0	0.3
Fuglestad et al. (1996): two-dimensional model including CH <sub>4</sub> feedbacks and tropospheric O <sub>3</sub> production by CO itself	10	3.0	1.0
Johnson and Derwent (1996): two-dimensional model including CH <sub>4</sub> feedbacks and tropospheric O <sub>3</sub> production by CO itself	----	2.1	----

**NO<sub>x</sub> and Non-Methane Hydrocarbons:** The short lifetimes and complex non-linear chemistries of NO<sub>x</sub> and NMHC make calculation of their indirect GWPs a challenging task subject to very large uncertainties. Through production of tropospheric O<sub>3</sub>, emissions of NO<sub>x</sub> lead to a positive radiative forcing of climate (warming), but by affecting the concentration of OH they reduce the levels of CH<sub>4</sub>, providing a negative forcing (cooling) which partly offsets the O<sub>3</sub> forcing. IPCC (2001) has reported the relative differences in the impacts of NO<sub>x</sub> upon O<sub>3</sub> depending on where it is emitted (in particular, surface emissions versus those from aircraft). Higher altitude emissions have greater impacts both because of longer NO<sub>x</sub> residence times and more efficient tropospheric O<sub>3</sub> production, as well as enhanced radiative forcing sensitivity. Two-dimensional model studies (Fuglestad et al., 1996; Johnson and Derwent, 1996) have presented estimates of the GWPs for NO<sub>x</sub> emitted from aircraft on the order of 450 considering a 100-year time horizon, while those for surface emissions are likely to be

much smaller, on the order of 5. It should be noted that such numerical values are subject to very large quantitative uncertainties. Similarly, NMHCs have a small direct radiative forcing. As indicated by Johnson and Derwent (1996), the indirect forcing through changes in OH and tropospheric O<sub>3</sub> is also small for each NMHC taken individually but can be significant taken as a family. The indirect forcings of NMHCs are still poorly quantified and require the use of global three-dimensional chemical transport models. Accurate calculations of these effects are a notoriously difficult problem in atmospheric chemistry.

#### D. Pollutants Included in the Proposed Regulation

Assembly Bill 1493 (Pavley, 2002) calls for reductions in GHGs which are defined as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The first four of these identified global climate change pollutants are clearly associated with motor vehicle use in California whereas perfluorocarbons and sulfur hexafluoride are not known to be associated with motor vehicle emissions in California and therefore are not addressed further in the staff report.

Black carbon and criteria pollutant emissions from motor vehicles are also known to have global climate change impacts. Although these pollutants are not specifically defined as greenhouse gases in AB 1493, the authority to regulate these pollutants currently exists in the Health and Safety Code (Section 39014). AB 1493 does not limit that authority; rather it supports the need to address the impacts of climate change pollutants.

The 2001 IPCC states that in addition to the gases targeted in the Kyoto Protocol, the contribution of tropospheric O<sub>3</sub> to the greenhouse effect is also important. The report further states that in order to curb global warming it is necessary to reduce the emissions of both GHGs and other gases that influence the concentration of GHGs. Air pollutants such as NO<sub>x</sub>, CO, and NMVOC produce OH radicals, that affect tropospheric O<sub>3</sub> and CH<sub>4</sub> levels, and hence they are called indirect GHGs. However, due to the basic uncertainties regarding the actual impact of criteria pollutant emissions on climate, it is impossible at this time to have confidence in any numerical prediction of the climate effect of their emissions from light-duty motor vehicles. Because the uncertainties associated with the impact of criteria pollutants on climate change are large, at this time the ARB has chosen not to consider the potential climate change effects when regulating CO, NO<sub>x</sub>, VOC or aerosols. However, as more definite scientific evidence becomes available, the ARB will, if appropriate, consider the climate change impacts of these criteria pollutants in its regulatory decisions.

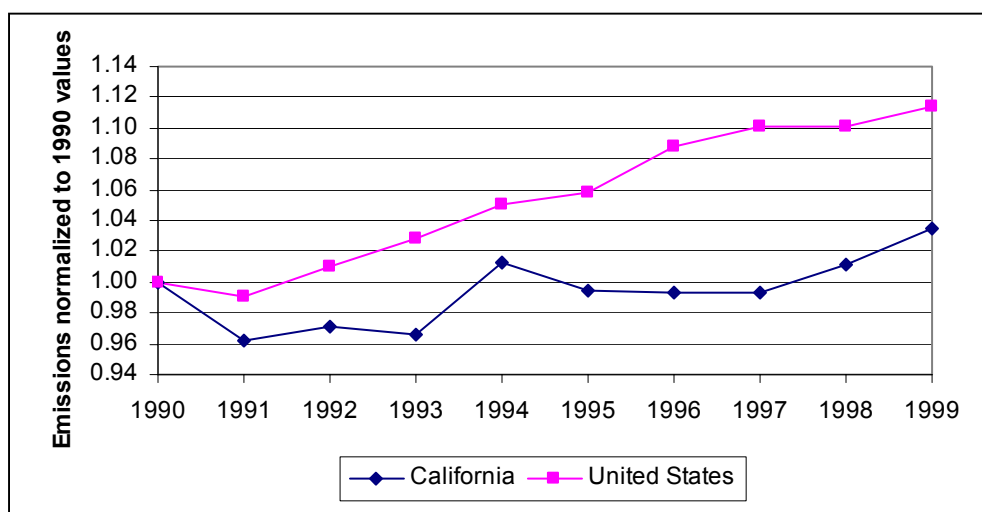
#### E. Indicators of Climate Change In California

The climate is changing under the influence of human activity. Climate change indicators can be used to illustrate trends, measure the suitability of particular actions in certain areas and encourage public awareness of the climate change impacts. Several potential climate change indicators have been suggested, including anthropogenic GHG emissions, air temperature, annual Sierra Nevada snow melt runoff, and sea level rise in California (EPIC, 2002).

Time series of historical emissions of anthropogenic GHGs have been produced for a

number of geographical regions. The GHGs emissions trends illustrate that, although California has been able to moderate its GHG emissions, total GHG emissions are still increasing and continue to remain above 1990 levels. With a relatively temperate climate, California uses relatively less heating and cooling energy than other states. However, California leads the nation in vehicle miles traveled, which leads to a concomitant increase in carbon dioxide emissions in the transportation sector. Tracking California's trends in motor vehicle-related GHGs emissions will allow an assessment of the State's contributions to global GHG emissions.

Figure 4 depicts overall trends in gross GHG emissions in California and the United States. Gross emissions include emissions from all the in-state and United States sources normalized to 1990 levels (i.e., gross emissions in each year are presented as a ratio of gross emissions in 1990) to allow a comparison between emissions in California and the United States. The emissions decline in California in 1991 and 1992 is in large measure the result of the economic recession experienced during those years. In 1994, emissions were relatively high because: 1) a recovering economy resulted in increased industrial activity and 2) low rainfall reduced availability of hydroelectric power, which in turn resulted in increased emissions from fossil-fueled electricity generation. Although moderated by availability of hydroelectric power, emissions from 1995 to 1999 increased from a strong expansion in the economy.



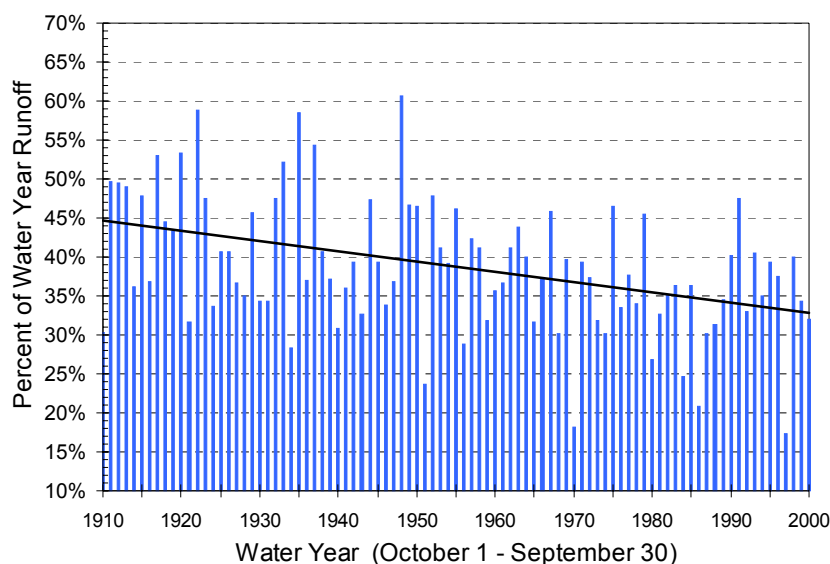
**Figure 4:** 1990-1999 relative gross greenhouse gas emissions (adapted from CEC, 2002)

Increases in the concentrations of GHG are predicted to change regional and global climate-related parameters such as temperature, precipitation, soil moisture, and sea level. Temperature data have been collected at many weather stations in the State for almost a century. The air temperature indicator can be used to track trends in Statewide surface air temperatures and regional variations, allowing for a comparison of temperature changes in California with those occurring globally. Analysis of annual mean air temperature at 93 California stations indicates that air temperature has increased over the past 90 years, more so in large cities than towns. Land use has an

impact on temperature and large urban areas are generally warmer than rural areas, and can have temperatures up to 5° F higher, creating their own warm belt.

The warming of global climate could increase evaporation rates, thereby potentially increasing precipitation and storms in the State. The yearly ratio of rain to snow depends on temperature, as does snow level elevations. The warmer the storm temperature, the higher the elevation at which snow falls and accumulates. Higher elevations of the snow line mean reduced snow pack and lower spring water yields. Snowmelt and runoff volume data can be used as a climate change indicator to document changes in runoff patterns. These changes are, at least in part, due to increased air temperatures and climate changes.

In California, large accumulations of snow occur in the Sierra Nevada and southern Cascade Mountains from October to March. Each winter, at the high elevations, snow accumulates into a deep pack, preserving much of California's water supply in cold storage. Spring warming causes snowmelt runoff, mostly during April through July. If the winter temperatures are warm, more of the precipitation falls as rain instead of snow, and water directly flows from watersheds before the spring snowmelt. Thus, there is less buildup of snow pack; as a result, the volume of water from the spring runoff is diminished. Lower water volumes of the spring snowmelt runoff may indicate warmer winter temperatures or unusually warm springtime temperatures. Figure 5 shows that throughout the 20<sup>th</sup> century, annual April to July spring runoff in the Sierra Nevada has been decreasing. This decreased runoff was especially evident after mid-century, since then the water runoff has declined by about ten percent (Roos, 2002).

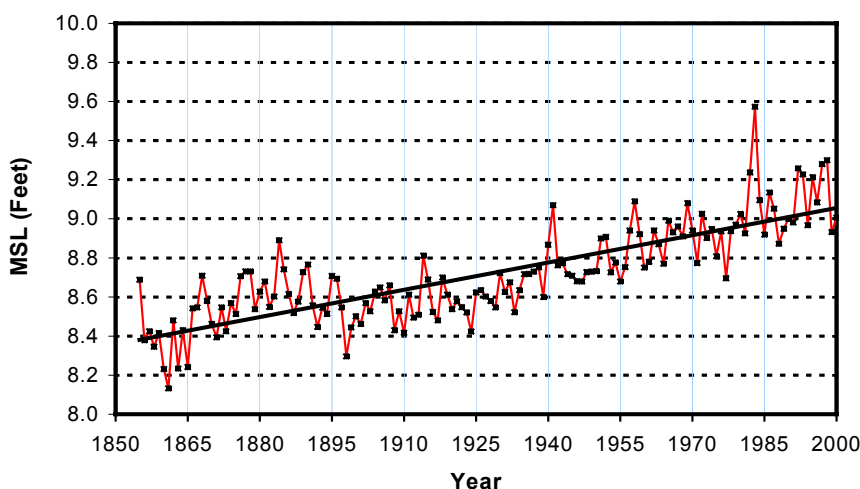


**Figure 5.** Sacramento river runoff (1910-2000) - April to July as a percent of total runoff (Roos, 2002).

Sea level rise also provides a physical measure of possible oceanic response to climate change. The rise in sea level may be associated with increasing global temperatures. Based on results from modeling, warming of the ocean water will cause a greater volume of sea water because of thermal expansion. This is expected to contribute the



largest share of sea level rise, followed by melting of mountain glaciers and ice caps (IPCC, 2001). Along California's coast, sea level already has risen by three to eight inches over the last century. Long-term data from 10 of 11 California stations show increases in sea level (Figure 6, using San Francisco as an example).



**Figure 6.** 1855-2000 San Francisco yearly mean sea level (Roos, 2002).

While the rates of increase vary, sea level is increasing almost everywhere in California (Flick, 1999). Sea level rise and storm surges could lead to flooding of low-lying areas, loss of coastal wetlands such as the San Francisco Bay Delta, erosion of cliffs and beaches, saltwater contamination of groundwater aquifers and drinking water, and damage to roads, causeways, and bridges. California's hundreds of miles of scenic coastline contain ecologically fragile estuaries, expansive urban centers, and fisheries that could be impacted by future changes in sea level elevation. Sea level rise could have serious impacts on the water resources of California.

With sea level rise there would be a serious impact to the California water supply in the Sacramento-San Joaquin River Delta. There would be problems with the levees protecting low-lying land, such as Delta islands, where the land subsidence has resulted in lands well below sea level, and increased salinity intrusion from the ocean, which could degrade fresh water transfer supplies pumped at the southern edge of the delta (Roos, 2000). Many Delta levees are built on peat soil foundations. The impact of sea level rise on these levees depends on the rate. A small rise can probably be tolerated; a major rise could cause significant problems. A substantial rise in sea level over the next century could challenge the continued viability of the 1,100-mile system of Delta levees, and would add greatly to the cost of maintaining these levees.

The climate change indicators described in this report represent key properties of the climate system that are considered sensitive to climate change. Many additional potential indicators remain to be explored. For example, climate change may influence the frequency of extreme weather events, ecosystem structures and processes, and species distribution and survival. It may affect forestry, energy and other industries,

insurance and other financial services, and human settlements. In addition, the impacts can vary from one region, ecosystem, species, industry, or community to the next. Research into the regional impacts of climate change is ongoing, and the potential climate change indicators will be updated and be expanded, as new information becomes available.

#### F. Potential Impacts on California

Climate is a central factor in Californian life. It is at least partially responsible for the State's rapid population growth in the past 50 years, and largely responsible for the success of industries such as agriculture and tourism. The potential effects of climate change on California have been widely discussed from a variety of perspectives (Lettenmaier and Sheer 1991; Gleick and Chalecki 1999; Wilkinson 2002). The signs of a global warming trend continue to become more evident and much of the scientific debate is now focused on expected rates at which future changes will occur. Rising temperatures and sea levels, and changes in hydrological systems are threats to California's economy, public health, and environment. The following section provides examples of why the State is particularly at risk from an increasingly warmer and more variable climate.

**Human Health and Air Pollution:** Human health in the California region is likely to be impacted by climate change. Several recent studies have addressed potential implications for human health at the national and international levels (Patz et al., 2000). Greater climate variability and changes in climate patterns would potentially cause both direct and indirect health effects. Direct health impacts due to climate change include extreme events, such as heat waves, droughts, increased fire frequency, and increased storm intensity resulting in flooding and landslides. Secondary or indirect health effects include damages to infrastructure causing, for example, sanitation and water treatment problems leading to an increase in water-borne infections. Air quality impacts such as increases in tropospheric (i.e., ground level) ozone due to higher temperatures may also cause secondary health impacts.

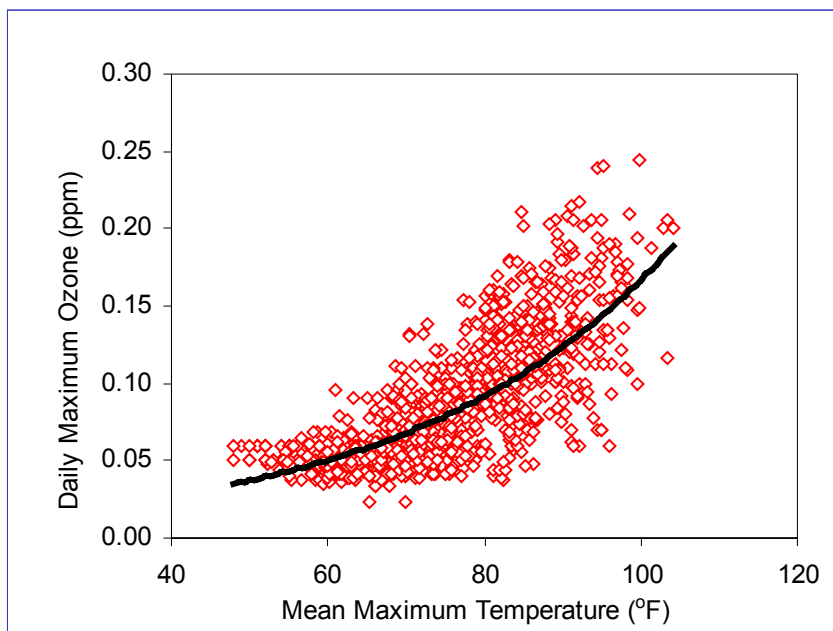
The most obvious direct impact of climate change is higher temperatures and increased frequency of heat waves which may increase the number of heat-related deaths and the incidence of heat-related illnesses. Cities such as Los Angeles that experience occasional very hot, dry weather may be especially susceptible. Studies of heat waves in urban areas have shown an association between increases in mortality and increases in heat, measured by maximum or minimum temperature, heat index (a measure of temperature and humidity), or air-mass conditions (Semenza et al., 1996). For example, after a 5-day heat wave in 1995 in which maximum temperatures in Chicago ranged from 93 to 104°F, the number of deaths increased 85 percent over the number recorded during the same period of the preceding year. At least 700 excess deaths (deaths beyond those expected for that period in that population) were recorded, most of which were directly attributed to heat (Semenza et al., 1999).

Until recently, excess deaths occurring during heat waves have been attributed entirely to heat-induced stress. However, analyses in the Netherlands (Fischer et al., 2004) and the United Kingdom (Stedman, 2004) conclude that a substantial portion of the mortality is actually due to elevated O<sub>3</sub> and particulate matter levels. Fischer et al. (2004)

estimate 400-600 excess air pollution-related deaths occurred in the Netherlands during June-August 2003 compared to 2000 and 2002. These values are almost half of the 1000-1400 total excess deaths estimated for summer 2003. The UK Office of National Statistics reported an excess of 2045 deaths in England and Wales for August 4-13, 2003 in comparison to the 1998-2002 average for that time of year. Stedman (2004) estimates that 21-38 percent of the total excess deaths are due to the elevated ozone and PM10 levels that occurred during the heat wave.

Air quality has a very real and direct effect on the health of many Californians who experience the worst air quality in the nation. Over 90 percent of Californians are living in areas that violate the State ambient air quality standard for ozone and/or particulate matter. In the Los Angeles area, population density, cars, climate, and geography conspire to create some of the nation's worst air quality. A study by Kinney and Ozkaynak (1991) of urban air pollution in Los Angeles County found a significant association between daily mortality and ozone levels. Other California cities including Bakersfield and Fresno are also struggling with severe air quality problems as the San Joaquin Valley (SJV) suffers from air pollution from various sources.

Climate change can lead to changes in weather patterns that can influence the frequency of meteorological conditions conducive to the development of high pollutant concentrations. High temperatures, strong sunlight, and stable air masses tend to increase the formation of ozone and secondary organic carbon particles – weather conditions associated with warmer temperatures increase smog. Figure 7 shows the relationship between ozone and temperature in the South Coast Air Basin.



**Figure 7.** Relationship between ozone and temperature in the South Coast Air Basin, 1996-1998

Air pollution is also made worse by increases in biogenic hydrocarbon emissions and evaporative emissions of fuels and solvents which leads to higher levels of ozone and

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PM<sub>10</sub> during hot weather. During hot summer days in California, air conditioners are used more frequently leading to increasing demands for electric power production and an associated increase in power plant emissions of NO<sub>x</sub>, hydrocarbons, and PM.

The interrelation of climate change and air quality has been investigated by several researchers. The premise of several studies (e.g., Sillman and Samson 1995, Taha and Bornstein, 1999; Taha et al., 2000) is that ozone air quality is profoundly affected by changes in climate and meteorology. Temperature, winds, solar radiation, atmospheric moisture, venting and mixing affect both the photochemical production of smog as well as the emissions of ozone precursors (e.g., NO<sub>x</sub> and VOC) that are temperature- and solar-radiation-dependent. For example, biogenic hydrocarbon emissions are particularly sensitive to changes in air temperature and solar radiation. In addition, meteorology affects the transport, dispersion, and deposition of pollutants and precursors alike.

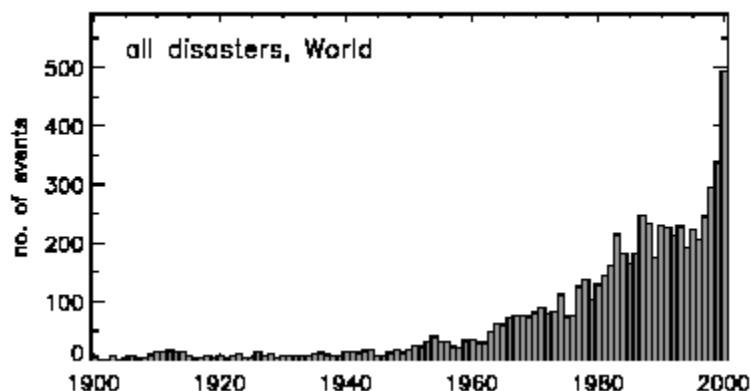
The direct effect of temperature variability on ozone and fine PM concentrations in Southern California was investigated by Aw and Kleeman (2003). Results indicate that the concentration of ozone and non-volatile secondary PM will generally increase at higher temperatures due to increased gas-phase reaction rates. The concentration of semi-volatile reaction products also will increase at higher temperatures, but the amount of this material that partitions to the particle-phase may decrease as the thermodynamic equilibrium between nitric acid, ammonia and ammonium nitrate favors the gases under warm, dry conditions. The role of temperature in pollutant emissions was not considered in this study.

There has been some focus on the potential impacts of changes (e.g., increases) in air temperature on ozone air quality. Air temperature has a direct effect on the photochemical reactions producing ozone, e.g., chemistry of PAN (Sillman et al., 1990) as well as emissions of precursors. But temperature is also an indirect indicator of other mechanisms that can accelerate smog formation. These include stalled high-pressure systems, intensified subsidence, reduced cloud cover, increased atmospheric water vapor, etc. Thus in this sense, temperature is a surrogate for many other exacerbating factors.

Climate change may alter the frequency, timing, intensity, and duration of extreme weather events (i.e., meteorological events that have a significant impact on local communities). Injury and death are the direct health impacts most often associated with natural disasters. Secondary health effects may also occur. These impacts are mediated by changes in ecological systems and public health infrastructures, such as bacterial proliferation and the availability of safe drinking water. Changes in precipitation, temperature, humidity, salinity, and wind have a measurable effect on the quality of water used for drinking, recreational, and commercial use, and as a source of fish and shellfish. Direct weather associations have been documented for waterborne disease agents such as *Vibrio* bacteria (Motes et al., 1998), viruses (Lipp et al., 1999), and harmful algal blooms (Harvell et al., 1999)

From 1945 to 1989, 145 natural disasters caused 14,536 deaths in the United States, an average of 323 deaths/year (Glickman and Silverman, 1992). According to the National Weather Service (NWS) report severe storms caused 600 deaths and 3,799

reported injuries in 1997. Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the United States; the average annual loss of life is estimated to be as high as 146 deaths per year. Brooks and Adger (2003) used data relating to natural disasters for the assessment of recent historical and current risk associated with climatic variability. The data are derived from the Emergency Events Database developed by the US Office of Foreign Disaster Assistance and the Center for Research into the Epidemiology of Disasters at the Université Catholique de Louvain in Brussels, Belgium (<http://www.cred.be/emdat>) as well as population data from the World Bank. Their results indicate that the broad trend in recorded disaster occurrence is one of increasing frequency in the latter half of the century (Figure 7). This is likely to be the result of several factors such as increases and improvements in reporting, population growth and increased population in areas subject to climate-related disasters (Berz, 1997). Climate change could have played significantly in increasing the frequency of disasters (Augusti et al., 2001; Frich et al., 2002).



**Figure 8.** Annual global frequency of recorded climate-related disasters for all disaster types (adapted from Brooks and Adger, 2003).

Indirect health effects of climate change include increases in the potential transmission of vector-borne infectious diseases caused by the extensions of ranges and seasons of some vector organisms and acceleration of the maturation of certain infectious parasites. Diseases transmitted between humans by blood-feeding arthropods (insects, ticks, and mites), such as plague, typhus, malaria, yellow fever, and dengue fever were once common in the United States and in Europe. Many of these diseases are no longer present in the United States, mainly because of changes in land use, agricultural methods, residential patterns, human behavior, and vector control. The ecology and transmission dynamics of these vector-borne infections are complex and the factors that influence transmission are unique to each disease. Most vector-borne diseases exhibit a distinct seasonal pattern which clearly suggests that they are weather sensitive. Rainfall, temperature, and other weather variables affect in many ways both the vectors and the pathogens they transmit. In California, as in much of the world there is concern that increased heat and moisture will facilitate the spread of emerging infectious

diseases, many of which are vector-borne. It has also been suggested that climate change will increase exposure to natural allergens. Fungi have adapted to virtually all environments, but fungal growth is often enhanced at increased temperature and/or humidity (Bernard et al., 2001).

In summary, serious effects on human health may result from climate change. It is clear that heat waves and other extreme events pose serious public health concerns. Higher temperatures are also likely to negatively affect health by exacerbating air pollution. The elderly, infirm, and poor are most at risk because heat and poor air quality can exacerbate pre-existing disease. Lack of access to air conditioning increases the risk of heat-related illness. Secondary or indirect effects of changes in climate such as changes in disease vectors may also pose concerns. Poor and immigrant populations (residence in urban areas where the heat island effect actually increases warming and the consequent effects of heat) are more vulnerable to climate change as they are often without adequate resources to control their environment with appliances such as air conditioners, or to seek medical attention. Thus, these communities are the first to experience negative climate change impacts like heat death and illness, respiratory illness, infectious disease, and economic and cultural displacement.

**Water Resources:** Much of California is semi-arid and, thus, water resources are a key factor in the State's economic and environmental well-being. Water resources are affected by changes in precipitation as well as by temperature, humidity, wind, and sunshine. Water resources in drier climates, such as California, tend to be more sensitive to climate changes. Because evaporation is likely to increase with warmer climate, it could result in lower river flows and lake levels, particularly in the summer. In addition, changes in meteorology could result in more intense precipitation which could increase flooding. If streamflow and lake levels drop, groundwater also could be reduced. The seasonal pattern of runoff into California's reservoirs could be susceptible to climatic warming. Winter runoff most likely would increase, while spring and summer runoff would decrease. This shift could be problematic, because the existing reservoirs are not large enough to store the increased winter flows for release in the summer. Increased winter flows to San Francisco Bay could increase the risk of flooding (Gleick and Chalecki 1999; Miller, et al., 2001; Roos 2002).

The California Department of Water Resources recognizes that climate change and variability can have important consequences for the State's water resource systems. Warmer temperatures combined with increased variation in the timing and quantity of precipitation can significantly influence the snowpack in the Sierra Nevada Mountains, water runoff patterns, water supply and demand, water temperatures, hydroelectric power production, wildfires, and soil moisture and groundwater levels. Increased severe weather events like the 1996-97 storm in California highlighted the State's vulnerability to climate variability and the need to prepare for the possibility of increases in frequency of extreme weather events.

California is home to about 35 million people. Using the California Department of Finance projections, it is estimated that California's population will grow by an average of 1.4 percent per year over the next 20 years. This projection translates to approximately 10 million more Californians by 2020.

The combination of population growth and climate warming could impose serious environmental challenges. Increased water demands and decreased water availability raise substantially the costs of providing water to urban, agricultural, and hydropower users. It is possible that California's water system could adapt to the population growth and climate change impact. However, even with new technologies for water supply, treatment, and water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, State, and federal government, this adaptation most likely will be costly.

**Agriculture:** If California's water resource systems face challenges from climate change and variability, so will the State's agricultural sectors. While agricultural production is vulnerable to climate change risks associated with adverse water system impacts, this sector faces other risks that come with increasingly unpredictable variations in both temperature and precipitation. For example, increases in the frequency of extreme weather at inopportune times can cause significant declines in agricultural productivity (Wilkinson, 2002).

California is the leading agricultural State in the U.S. by a considerable margin. The State has the most diverse crop mix of any region in the country. California has produced the highest agricultural crop value in the U.S. for more than 50 consecutive years. 28 million acres in California are involved in some form of agriculture. The impacts of global warming on crop yields and productivity will vary considerably by region. But several studies, including one by the US Department of Agriculture, show that maintaining today's levels of agricultural productivity would be difficult. At best, this would require expensive adaptation strategies. Farmers will likely need to change crops and cultivation methods because warming generally hinders crop yields, although the beneficial effects of elevated CO<sub>2</sub> in fertilizing plant growth may cancel out the effects of warming. If climate warming is accompanied by increased drought, however, the detrimental effects would be intensified.

In California, 87 percent of the crop area is irrigated, and increased drought could be countered by human management. Yet there are severe constraints on increased irrigation since 100 percent of the surface water is already allocated. Agricultural water users in the Central Valley are the most vulnerable to climate warming. While wetter hydrologies could increase water availability for these users, the driest climate warming hydrology could significantly reduce agricultural water deliveries in the Central Valley. If the climate shifts toward a severe drought, not only will more irrigation be needed, but also the snow pack at higher elevations will be lacking. This can be disastrous for producers that grow fruit trees and vines that will require years to reestablish production.

Growers of perennial crops, including fruits, nuts, and grapes, cannot shift quickly to new cultivars as conditions change. They are most vulnerable to shifts in climate and to extreme events such as drought or pest outbreaks. The economics of producing and selling crops will depend on the impacts of global climate change on worldwide agricultural markets.

**Ecological Impacts:** California is an ecologically diverse state, with 134 endangered and threatened species, including the sea otter, the California condor, and the American bald eagle. California's unique ecosystems include 25,000 square miles of desert. California's mountain ecosystems in the Sierra Nevada, including Yosemite National Park, contain alpine wilderness areas with large numbers of sequoia trees. The ranges of many species of plants and animals are restricted and fragmented because of both natural and human causes. Many invading species have colonized large areas and displaced native species in the wake of environmental changes in recent centuries (Wilkinson and Rounds, 1998).

Potential responses of California ecosystems to climate change fall generally into three categories. The response may be geographic; the boundaries between ecosystem types will move and the character of landscapes will inevitably change along with shifts in climate. The responses may involve changes in the way ecological processes work and in the goods and services that ecosystems supply to human societies (such as purification of air and water, decomposition of wastes, maintenance of soil fertility, control of pests, pollination services, recreational opportunities, plant productivity, the health of fisheries). Finally, the responses may entail changes in the kinds of plants and animals that live in a community, and these necessarily lead to changes in how the ecosystem works. All three types of responses are interrelated (Field et al., 1999). Changes in climate have the potential to affect the geographic location of ecological systems, the mix of species that they contain, and their ability to provide the wide range of benefits on which societies rely for their continued existence. Ecological systems are intrinsically dynamic and are constantly influenced by climate variability. The primary influence of anthropogenic climate change on ecosystems is expected to be through the rate and magnitude of change in climate means and extremes.

Climate change could have an impact on many of California's species and ecosystems. For example, aquatic habitats are likely to be significantly affected by climatic changes. Most fish have evolved to thrive in a specific, narrow temperature range. As temperatures warm, many fish will have to retreat to cooler waters. Species differ significantly in their abilities to disperse and to become established in new locations with more suitable climates. Poorly dispersed species, such as amphibians and oaks and related species, may not be able to survive the predicted rapid climatic changes if they have narrow tolerances for specific environmental conditions. Even for easily dispersed species, such as grasses and birds, other biological interactions (i.e., new predators, missing pollinators, lack of specific food sources) or physical environments (i.e., different soils, roads, lack of suitable intervening habitat) may block the success of migration.

With changes in climate, the extent of forested areas in California could also change. The magnitude of change depends on many factors, including whether soils become drier and, if so, how much. Hotter, drier weather could increase the frequency and intensity of wildfires, threatening both property and forests. Along the Sierras, drier conditions could reduce the range and productivity of conifer and oak forests. Farther north and along the northern coast, drier conditions could reduce growth of the Douglas fir and redwood forests. A significant increase in the extent of grasslands and chaparral



throughout the State could result. These changes would affect the character of California forests and the activities that depend on them.

The responses of California forest species to climate change will depend critically on changes in water supply and the availability of mineral nutrients in the soil. If water and nutrients are sufficient, elevated CO<sub>2</sub> is likely to enhance forest production. However, in forests, as in other California ecosystems, fires, pests, and pathogens have the potential to greatly affect how ecosystems respond to climate change; conceivably even reversing the predicted responses to elevated CO<sub>2</sub>. Adaptation options for ecosystems are limited, and their effectiveness is uncertain for this reason, and others such as the projected rapid rate of change relative to the rate at which species can reestablish themselves, the isolation and fragmentation of many ecosystems, the existence of multiple stresses (e.g., land-use change, pollution), and limited adaptation options, ecosystems (especially forested systems) are vulnerable to climate change.

**Impact on Economy:** California produces more than one-eighth of total U.S. economic output, which makes it equivalent to the fifth or sixth largest economy in the world. Increased climate variability and long-term climate change potentially will affect the state's sectors in important and different ways. Some activities and enterprises will be impacted directly through changes in natural resource and ecosystem services. Water shortages and increased insect predation of crops due to relatively rapid changes in insect populations, for example, will have direct impacts on the state's diverse agricultural sector. While field crops may be switched by the season, perennial crops including vineyards and orchards are long-term investments. The reported damages from the El Niño storms in 1997-98 for agricultural losses was approaching \$100 million. From dairy farmers losing cows to exhaustion as they try to escape the mud and are attacked by diseases, to strawberry growers losing crops to the rain, farmers have experienced significant losses due to strong climate variability (Wilkinson and Rounds, 1998).

Precipitation falling as rain instead of snow will pose major problems for water managers, as the existing capture will become inadequate, and distribution system designed for the current supply and demand areas will develop bottlenecks. Higher summer temperatures will cause more rapid deterioration of asphalt and concrete, impacting the highway and rail systems. Sea level increases of up to three feet over the next century, with consequent implications for coastal erosion, inundation of wetlands, salt water intrusion of coastal and delta aquifers, and impacts on developed areas would clearly be extremely costly to mitigate, and devastating to some ecosystems and urban communities.

The varied impacts of relatively rapid climate change, and increased variability in rainfall and temperatures, will have significant economic impacts upon California's many sectors. Rising costs for infrastructure maintenance, resources, and insurance will reduce California's economic competitiveness. Rapid changes and greater variability are generally more difficult and expensive to adapt to than slower changes and lower variability. Electric and water supply utilities, wastewater treatment systems, and transportation systems are all subject to very significant expenditures in response to challenges imposed by climate variability. Both storms and droughts cause hundreds of millions of dollars in preventive costs and in damages. Pacific Gas and Electric, for

example, allocated \$250 million in 1997 for tree trimming to reduce the incidence of power outages in its service area (Wilkinson and Rounds, 1998). Climate change has the potential to affect many aspects of California—the survival of its unique ecosystems, its ability to produce electricity, its supply of water and agricultural products, and the resources that support its economy.

### G. Abrupt Climate Change

When most people think about climate change, they imagine gradual increases in temperature and only marginal changes in other climatic conditions, continuing indefinitely or even leveling off at some time in the future. It is assumed that human societies can adapt to gradual climate change. However, recent climate change research has uncovered a disturbing feature of the Earth's climate system: it is capable of sudden, violent shifts. This is a critically important realization. Climate change will not necessarily be gradual, as assumed in most climate change projections, but may instead involve sudden jumps between very different states. A mounting body of evidence suggests that continued GHG emissions may push the oceans past a critical threshold and into a drastically different future. Abrupt climate change is the subject of a report commissioned by the U.S. Department of Defense (Schwartz and Randall, 2003). The report stated that abrupt climate change could destabilize the geo-political environment, leading to skirmishes, battles, and even war due to resources constraints such as food shortage, decreased availability and quality of fresh water, and disrupted access to energy supply.

Change in any measure of climate or its variability can be abrupt, including a change in the intensity, duration, or frequency of extreme events. For example, single floods, hurricanes, or volcanic eruptions are important for humans and ecosystems, but their effects generally would not be considered abrupt climate changes. However, a rapid, persistent change in the number or strength of floods or hurricanes might be an abrupt climate change. Although more regionally limited, the apparent change in El Niño behavior (Graham, 1994; Trenberth and Hoar, 1996) could also be considered an abrupt change. El Niño is characterized by a large-scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño is notorious worldwide for causing catastrophic disruptions in weather patterns. Floods in California are countered by droughts in Australia.

Abrupt changes in climate are most likely to be significant, from a human perspective, if they persist over years or longer, are larger than typical climate variability, and affect sub-continental or larger regions. The simplest concept for a mechanism causing abrupt climatic change is that of a threshold. A gradual change in external forcing or in an internal climatic parameter continues until a specific threshold value is reached at which point a qualitative change in climate is triggered. Various such critical thresholds are known to exist in the climate system (NRC, 2002). Continental ice sheets may have a stability threshold where they start to surge; the thermohaline ocean circulation has thresholds where deep water formation shuts down or shifts location; methane hydrates in the seafloor have a temperature threshold where they change into the gas phase and bubble up into the atmosphere; and the atmosphere itself may have thresholds where large-scale circulation regimes switch.

Researchers first became intrigued by abrupt climate change when they discovered striking evidence of large, abrupt, and widespread changes preserved in paleoclimatic archives. Paleoclimatology is the study of past changes in the climate system. Interpretation of such proxy records of climate, for example, using tree rings to judge occurrence of droughts or gas bubbles in ice cores to study the atmosphere at the time the bubbles were trapped, is a well-established science that has seen much growth in recent years. Recent scientific evidence (NRC, 2002) shows that major and widespread climate changes have occurred with startling speed. For example, roughly half the north Atlantic warming since the last ice age was achieved in only a decade, and it was accompanied by significant climatic changes across most of the globe. Similar events, including local warming as large as 16 ° C, occurred repeatedly during the slide into and climb out of the last ice age.

It is almost certain that there are nonlinearities in the climate system that could have caused abrupt climatic changes in the past or may do so in the future. Significant anthropogenic warming of the lower atmosphere and ocean surface will almost certainly occur in this century, raising concerns that nonlinear thresholds in the climate system could be exceeded and abrupt changes could be triggered at some point. Processes that have been mentioned in this context include a collapse of the West Antarctic Ice Sheet, a strongly enhanced greenhouse effect due to melting of permafrost or triggering of methane hydrate deposits at the seafloor, a large-scale wilting of forests when drought tolerance thresholds are exceeded, nonlinear changes in monsoon regimes, and abrupt changes in ocean circulation. The probability of major climatic thresholds being crossed in the coming centuries is difficult to establish and largely unknown. Currently, this possibility lies within the uncertainty range for future climate projections, so the risk cannot be ruled out.

One proposed response to climate change assumes that modern civilization will adapt to whatever weather conditions we face and that the pace of climate change will not overwhelm the adaptive capacity of society, or that our efforts such as those embodied in the Kyoto Protocol will be sufficient to mitigate the impacts. Optimists assert that the benefits from technological innovation will be able to outpace the negative effects of climate change. Societies have faced both gradual and abrupt climate changes for millennia and have learned to adapt through various mechanisms, such as developing irrigation for crops, and migrating away from inhospitable regions. Nevertheless, because climate change will likely continue in the coming decades, denying the likelihood or downplaying the relevance of past abrupt events could be costly. Thus, in addition to the gradual (albeit accelerated) climate changes projected by current climate models, Californians need to be aware of the possibility of much more sudden climate shifts. These shifts have a scientifically well-founded place among the possible futures facing the State and should be among the possibilities accommodated in planning and adaptation measures.

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### **Attachment A: Aerosol Particles and Climate Change**

Atmospheric aerosols refer to solid or liquid phase material suspended into air. Aerosol particles or particulate matter (PM) is not a single pollutant, but rather a mixture of many subclasses of pollutants with each subclass potentially containing many different chemical species. Particles may be either directly emitted into the atmosphere (primary particles) or formed there by chemical reactions of gases (secondary particles) from natural and anthropogenic sources such as sulfur dioxide (SO<sub>2</sub>), oxides of nitrogen (NO<sub>x</sub>), and certain organic compounds. The relative importance of primary and secondary particles generally depends on the geographical location with precursor emissions, atmospheric chemistry, and meteorology all playing a role. Examples of PM include combustion-generated particles, such as those from automobiles or wood burning; photochemically-produced particles, such as those found in urban haze; salt particles formed from sea spray; and soil-like particles from resuspended dust. Airborne particles have been extensively studied because of the adverse health effects and poor visibility they cause; however, PM also has an effect on climate.

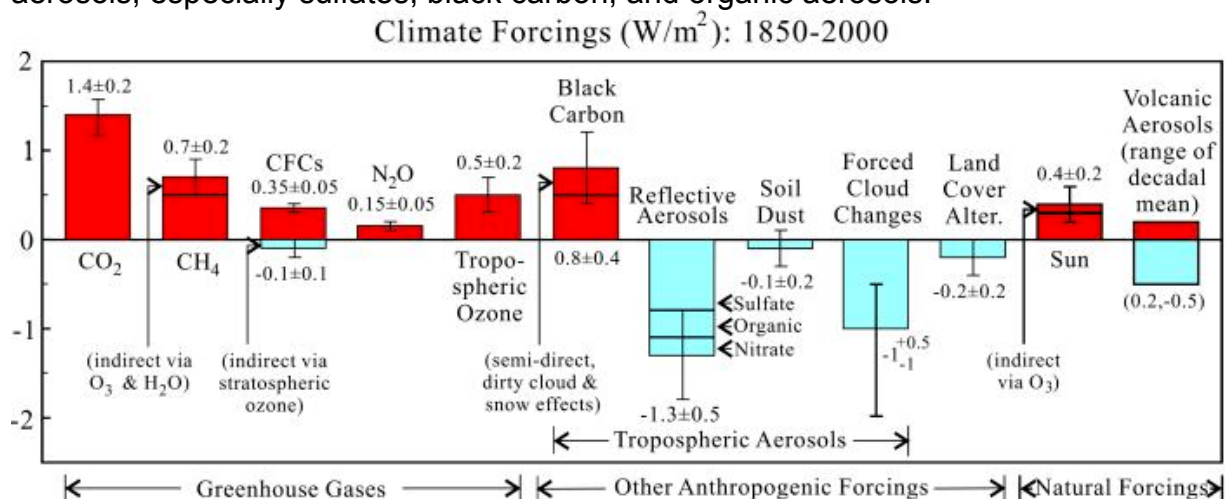
With respect to climate change the initial focus of concern, both scientifically and for managing climate, was on so-called greenhouse gases – carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), etc. – but research over the last two decades has demonstrated that particles, too, have the potential to significantly alter climate processes. Particles impact climate directly by modifying Earth's radiation balance through their interaction with both long wave (infrared) and short wave (visible) light, and indirectly by their role as condensation nuclei in cloud formation. This effect is termed "radiative forcing." Depending on chemistry, timing, and location, particles may either heat or cool the atmosphere. Positive radiative forcing warms the Earth's surface and lower atmosphere. Conversely, negative radiative forcing has a cooling effect. Natural factors, such as changes in solar output, explosive volcanic activity, snow, or cloud cover can also have radiative forcing effects. The planetary radiation balance is the net sum of all positive and negative forcing occurring together. Thus an effect such as climate warming by positive infrared forcing due to increasing greenhouse gases concentrations may be offset by negative forcing due to visible light scattering by "white" aerosols (e.g., sulfates) or enhanced by warming due to infrared and visible light absorption by "black carbon" or soot.

The chemical composition and optical properties of aerosols vary with their sources; for example, aerosols emitted into the air as urban industrial pollution influence the climate very differently from windblown desert dust or sea salt or biogenic aerosols. To further complicate this picture, aerosols tend to remain in the air for only a few days to a week or so, resulting in extreme spatial and temporal variability over the surface of the Earth. As a consequence, measuring or describing "typical" properties of aerosols, as well as quantifying their radiative impact on global and regional scales, is a daunting task.

Determining the impact of anthropogenic PM emissions on climate requires properly accounting for all radiative forcing, natural and manmade, then determining the shift in

net radiation that would occur if the anthropogenic component were removed, and finally calculating the change in climate that would result from that shift in radiation. While this is simple in concept, it is very difficult to implement because of lack of a proper inventory of all the aerosols in the Earth's atmosphere, knowledge of how much aerosol in the Earth's atmosphere is due to anthropogenic activity, knowledge of ambient aerosol distribution patterns with sufficient temporal and spatial resolution and how to partition secondary aerosol effects, such as cloud formation, between natural and anthropogenic aerosols, and having climate models with sufficient precision to reliably perform the climate effect calculation.

Figure 1 shows estimated worldwide climate forcing from all climate pollutant sources since 1850, measured in watts per square meter. The rectangular bars represent estimates of the contributions of different variables - some of which are positive and thus represent warming, other are negative and represent cooling. Climate forcing by CO<sub>2</sub> is the largest, but it does not dwarf the others. Forcing by non-CO<sub>2</sub> greenhouse gases approximately equals that of CO<sub>2</sub>. Moreover, in comparing forcing due to different activities, it should be noted that fossil fuel combustion is a major source of atmospheric aerosols, especially sulfates, black carbon, and organic aerosols.



**Figure 1.** Estimated climate forcing between 1850 and 2000 (Hansen et. al., 2000)

Climate forcing by anthropogenic aerosols may be the largest source of uncertainty about future climate change. Climate scientists do not even know the sign of the current impact of aerosol forcing, because such information would require knowledge of the trends of different aerosol compositions. For example, direct aerosol forcing depends on the aerosol's light scattering properties and on the amount of absorbing constituents. Aerosols also alter the formation and precipitation efficiency of liquid water, ice and mixed-phase clouds, thereby causing an indirect radiative forcing associated with these changes in cloud properties. The problem of estimating the indirect climate effect of atmospheric aerosols is a very complex one as many parameters need to be known to quantify it.

In addition to aerosol mass concentration, aerosol properties, such as number distribution and size-dependent composition and shape, exert a strong influence on important aerosol optical properties influencing the scattering and absorption of radiation. Specifically, the light scattering and absorption coefficients and the angular dependence of light scattering depend strongly on the size, shape, and real and imaginary components of index of refraction of the particles comprising the aerosol. Hygroscopic growth of aerosol particles (which itself strongly influences their optical properties) and the ability of particles to nucleate cloud droplets during cloud formation similarly depend on particle composition and size. Consequently, a description of aerosol influences on atmospheric radiation (direct effects), on cloud properties influencing radiation (indirect effects) or precipitation development (with concomitant removal of the aerosol material from the atmosphere) must explicitly or implicitly take into account the size-dependent composition of the particles comprising the aerosol in addition to mass concentration.

In principle aerosol mass concentration and the pertinent other aerosol properties might be determined by measurement. However such an approach to meeting the needs for representing aerosol influences on climate is a very complicated task for a variety of reasons. Sources of aerosols are very nonuniformly distributed, both in amount and in kind. Mean residence times of aerosols in the troposphere are short (about 1 week) compared to the time required to uniformly distribute material in a given hemisphere (about 1 year), and removal is quite intermittent, governed mainly by precipitation processes. Hence the spatial distribution of aerosol mass concentrations and properties in the atmosphere is quite nonuniform. Likewise, there is high temporal variation in aerosol mass concentration and properties mainly resulting from variability of synoptic scale meteorology which controls transport and removal but also to a considerable extent from variability of emissions. Hence, the measurement of aerosol properties by in-situ sampling at representative locations, as is done for the long-lived greenhouse gases, is not practical.

Even if it were possible by measurement to characterize the aerosol properties required to represent aerosol radiative influences in radiation transfer models, this information would still be insufficient to meet the requirements of modeling these influences at places and times other than those of the measurements. For example, climate modeling is required for past times, importantly over the last 200 years marking the growth of industrial emissions of CO<sub>2</sub> and other greenhouse gases. To accurately model anthropogenic influences on climate, it is necessary to determine the historical aerosol forcing as a component of the total climate forcing. Likewise it would not be possible on the basis of aerosol measurements alone to represent aerosol forcing in future time for various scenarios of emissions of aerosols and precursor gases.

The alternative to using measurements to determine aerosol loading and properties necessary to represent aerosol influences in climate models is to calculate these properties (as a function of location and time) by means of chemical transport models incorporating aerosol evolution processes. Although present modeling capability is still fairly rudimentary, this modeling approach, which consists of numerically representing

the processes governing the concentration and microphysical properties of these aerosols, appears to be the only viable means of obtaining this information, and it has served as the basis of estimates of aerosol forcing to date, such those reported by the IPCC (2001). The major aerosol classes are briefly described on the following pages.

**Sulfate:** The vast majority of sulfate aerosols are formed by the oxidation of gaseous sulfur compounds into sulfuric acid, which then combines with a metallic or alkaline ion to form a stable salt ( $\text{Na}_2\text{SO}_4$ ,  $\text{Mg}_2\text{SO}_4$ ,  $(\text{NH}_4)_2\text{SO}_4$ , etc.). Sulfate aerosols mostly form in heterogeneous (gas, droplet, and particle) atmospheric conversion, which tends to concentrate sulfate in fine aerosols ( $<2\text{ }\mu\text{m}$  diameter). When both humidity and sulfuric acid concentrations are high and sufficient neutralizing ions are not present, a liquid phase sulfuric acid aerosol can form.

Due to the hygroscopic nature of both sulfuric acid and sulfate salts, sulfate aerosols are prone to grow by accumulation of water, so that their effective optical cross section is enhanced far beyond the actual sulfate mass. Since sulfate aerosols are very efficient at scattering light, their impact on the Earth's radiation balance is predominantly negative forcing (cooling) due to backscatter of incoming solar radiation; this effect may be enhanced if their hygroscopicity contributes to increased daytime clouds or fog, or may be somewhat offset if they increase the presence of nighttime clouds or fog.

Of all the chemical species present as atmospheric aerosol, sulfate is considered to be the largest contributor to anthropogenic direct climate forcing. Direct radiative forcing by sulfate aerosols has received considerable attention over the past decade; estimates of global mean forcing range between  $-0.29$  and  $-0.95 \text{ W/m}^2$ . Disagreements over the atmospheric sulfate burden and the fraction of that burden that is caused by human activities accounts for some, but not all, of this uncertainty.

The importance of pollutant sulfate in climate change was only fully appreciated in the last decade; inclusion of sulfate cooling helped to reduce the gap between climate change predicted based on GHG calculations and observed secular temperature records (Charleson, et al., 1992). Future reductions in global pollutant sulfur emissions (necessary to manage impacts on public health and prevent "acid rain") may accelerate climate warming as the artificial cooling effect of sulfate is removed (IPCC, 2001).

The precursor sulfur compounds come from both natural and anthropogenic sources. Globally, most natural sulfate comes from biogenic production (primarily in the oceans), with volcanic emissions contributing modestly (e.g., hot springs and fumaroles) on a continuing basis, and occasionally very intensely (large eruptions). As a result, natural sulfate concentrations are somewhat higher over the oceans and lower over the continents. This tends to focus sulfate effects, suppressing solar input on the oceans (lowering heating and evaporation) while minimally altering radiation balance over continents. Large volcanic eruptions have been observed to cool the globe for months or years, an effect believed to be largely due to sulfate.

In the short term, volcanoes exert a net cooling effect at the surface due to their emissions of sulfur dioxide. That is because particles injected into the stratosphere (about 12 km above the Earth surface) absorb the sun's energy before it can reach the surface. The cooling effect depends on the composition of the volcanic emissions (particularly sulfur content) and on the location of the volcanoes (high latitude volcanoes - nearer to the poles - tend to have a greater effect because more of their emissions reach the stratosphere). Natural sulfate levels in the atmosphere have been estimated from observations and calculation of emissions, and their climatic effect estimated as well (Charleson, 1987).

Anthropogenic sulfate aerosol is generated through the same chemical pathways, but the precursor gases generally come from sulfur bound in fuels used in combustion processes (predominantly coal and petroleum). The potential effects of anthropogenic sulfate are strongest near industrialized regions where large amounts of fossil fuels are burned, thus the cooling effect is strongest over eastern North America, Europe, eastern Asia, and the oceanic and continental areas downwind of these regions (Charleson, 1992; IPCC, 2001).

**Nitrate:** Analogously to sulfate, nitrate aerosols form from the oxidation of gaseous nitrogen oxides followed by nitrate salt formation, and have similar optical properties. They are distinct from sulfate in that nitrate salts are unstable and can return to the vapor phase when air temperature rises and humidity drops or the surrounding air's concentration of precursor gases drops. The dynamics of nitrate aerosol formation and disappearance limit the scope of nitrate impacts on global climate processes.

Atmospheric aerosols contain significant amounts of nitrate in polluted areas. Both nitrate and sulfate are generally neutralized to a substantial degree by ammonia, which exists in the aerosol phase as the ammonium cation. Most importantly, inorganic aerosols are hygroscopic and contain water under nearly all atmospheric conditions. The amount of aerosol nitrate, ammonium, and water influence, with sulfate, affects the optical properties of the aerosol.

Of all these components, water plays perhaps the greatest role in determining aerosol optical behavior, simply because it constitutes most of the aerosol mass. Moreover, water uptake is highly nonlinear. Ammonium sulfate particles, for example, triple in volume as relative humidity (RH) increases from 85% to 95%, but grow by less than 20% from 50% to 60% RH. Water uptake also depends on the degree to which sulfate is neutralized by ammonia, with sulfuric acid being more hygroscopic than ammonium bisulfate or ammonium sulfate except near 100% RH. As a result, water uptake by inorganic aerosol is highly variable in time and space as relative humidity and aerosol composition change.

Adams et al. (2001) estimate the present-day anthropogenic direct aerosol forcing to be  $-0.95 \text{ W/m}^2$  for sulfate and  $-0.19 \text{ W/m}^2$  for nitrate. Moreover, based on the IPCC (2001) emissions scenario with especially strong increases in  $\text{NO}_x$  emissions, it is predicted that the nitrate forcing will increase to  $-1.28 \text{ W/m}^2$  by the end of this century, even while

sulfate forcing declines to  $-0.85 \text{ W/m}^2$ . This result shows that future estimates of aerosol forcing based solely on predicted sulfate concentrations may be misleading and that the potential for significant amounts of ammonium nitrate aerosol needs to be considered in estimates of future climate change.

A key finding is that the calculated direct forcing is extremely sensitive to how the effect of water uptake on aerosol scattering behavior is taken into account. In particular, Adams et al. (2001) find that the large amount of water taken up by the aerosol above 95% RH increases the total forcing by about 60%. This is important because a method commonly used in previous global climate models for parameterizing the effect of water uptake on optical properties has been to assume a low RH scattering coefficient and to correct for that at higher humidities with an empirical factor. In principle, there is nothing wrong with this approach, but in practice, lack of data at high RH has caused investigators to conservatively limit it to values that are unrealistically low.

**Mineral Dust:** “Mineral dust” is generally derived from soil surfaces, either as a result of natural or anthropogenic activities. Near-source mineral dust is composed of a variety of crystalline materials, including sand, fine rock fragments (“silt”), and clay particles. Sand and silt materials such as silica have high specific densities and generally fracture into compact shapes, thus coarse mineral particles ( $>5\mu\text{m}$  diameter) settle rapidly and have very short atmospheric lifetimes (minutes to hours). Conversely, clays, having sheet crystal structures and much smaller particle dimensions, have very large surface to mass ratios and very small settling velocities. Global “background” mineral aerosol is thus finer (mass median diameter near  $2\mu\text{m}$ ) and often chemically distinct from most local-source mineral PM. The lifetime of fine particles in the atmosphere is days or weeks, and they can travel by air thousands of kilometers.

While the precise fraction of mineral dust of anthropogenic origin being extremely difficult to determine, recent studies have suggested that 20% and up to 30 to 50% (Tegen and Fung, 1995) of the total mineral dust in the atmosphere originates from anthropogenic activities. In addition to the short-wave radiative forcing, mineral dust particles may exert a significant long-wave radiative forcing. The global mean short-wave radiative forcing will be negative due to the predominantly scattering nature in the solar spectrum (although partial absorption may lead to a local positive radiative forcing over high surface albedos and clouds) and the global mean long-wave forcing will be positive. Albedo is the fraction of solar energy (shortwave radiation) reflected from the Earth back into space.

Tegen and Fung (1995) performed a three-dimensional global climate modeling study of dust aerosol and estimated that approximately 30 to 50% of the total dust burden is due to changes in land use associated with anthropogenic activity. The radiative forcing using this data was estimated by Tegen et al. (1996) to be  $-0.25 \text{ W/m}^2$  in the short-wave and  $+0.34 \text{ W/m}^2$  in the long-wave, resulting in a net radiative forcing of  $+0.09 \text{ W/m}^2$ . Updated calculations of the net radiative forcing based on Miller and Tegen (1998) estimate the radiative forcing to be  $-0.22 \text{ W/m}^2$  in the short-wave and  $+0.16 \text{ W/m}^2$  in the long-wave, resulting in a net radiative forcing of  $-0.06 \text{ W/m}^2$ . Hansen et al. (1998)



perform similar calculations and calculate a net radiative forcing of  $-0.12 \text{ W/m}^2$  by assuming a different vertical distribution, different optical parameters and using a different global model. Jacobson (2001) used a multi-component global aerosol model to estimate the direct radiative forcing to be  $-0.062 \text{ W/m}^2$  in the short-wave and  $+0.05 \text{ W/m}^2$  in the long-wave, resulting in a net radiative forcing of  $-0.012 \text{ W/m}^2$ . The effects of non-sphericity of the mineral dust are not accounted for in these calculations. Mishchenko et al. (1997) suggest that differences in the optical parameters between model spheroids and actual dust particles do not exceed 10 to 15%, although changes of this magnitude may have a large effect on the radiative forcing.

One problem with modeling the impacts of mineral dust is uncertainty in representative refractive indices and how they vary geographically due to different mineral composition of different source regions. Additional uncertainties lie in modeling the size distributions which, together with the refractive indices, determine the optical parameters. Relating instantaneous observational measurements that do not account for the effects of clouds, diurnal averaging of the radiation, the seasonal signal associated with emissions and the fraction of mineral dust that is anthropogenic to the global mean radiative forcing is very difficult. Because the resultant global mean net radiative forcing is a residual obtained by summing the short-wave and the long-wave radiative forcings which are of roughly comparable magnitudes, the uncertainty in the radiative forcing is large and even the sign is in doubt due to the competing nature of the short-wave and long-wave effects. The studies above suggest, on balance, that the short-wave radiative forcing is likely to be of a larger magnitude than the long-wave radiative forcing, which indicates that the net radiative forcing is likely to be negative, although a net positive radiative forcing cannot be ruled out. Therefore, a tentative range of  $-0.6$  to  $+0.4 \text{ W/m}^2$  is adopted; a best estimate cannot be assigned as yet.

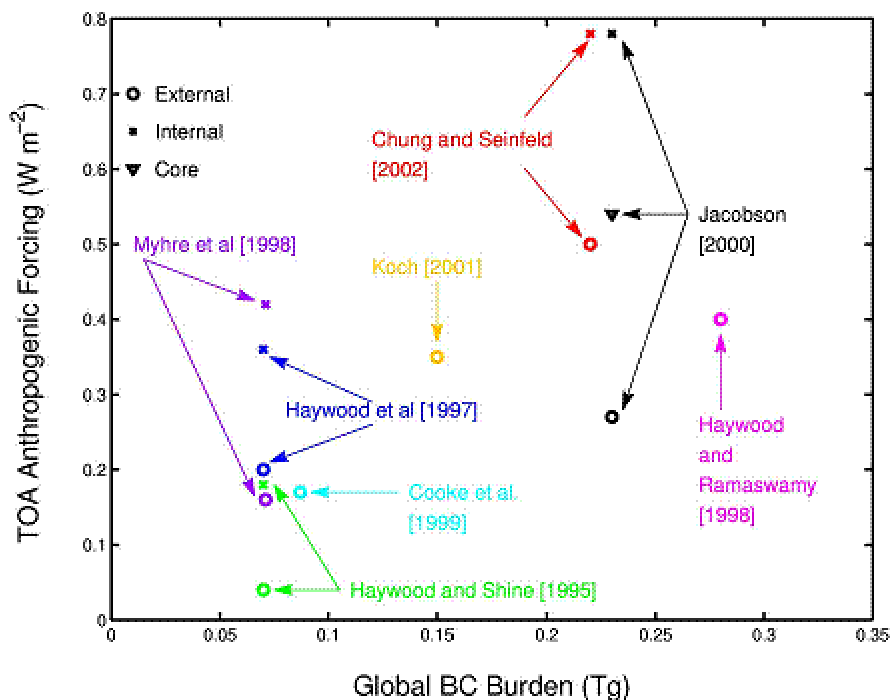
**Carbonaceous Particles:** Carbonaceous particulate matter consists of a complex mixture of chemical compounds. Such particulate matter is usually divided into two fractions, black (or elemental) carbon (BC) and organic carbon (OC). Black carbon is a strong absorber of visible and near-infrared light; therefore, BC concentrations are traditionally determined by light-absorption measurements of particles collected on filters (Lindberg et al., 1999). In contrast, particulate OC represents an aggregate of hundreds of individual compounds with a wide range of chemical and thermodynamic properties, making concentration measurements difficult using any single analytical technique. Instead, aerosol OC content is usually determined from the difference between total carbon and black carbon contents (Turpin et al., 2000).

Organic carbon can be emitted directly into the atmosphere as products of fossil fuel combustion or biomass burning. This is called primary organic aerosol (POA). By contrast, secondary organic aerosol (SOA) is formed in the atmosphere as the oxidation products of certain volatile organic compounds (VOCs) condense on pre-existing aerosols. Aerosol organic carbon, whether primary or secondary in nature, is not a strong absorber of solar radiation. As a result, from a climatic point of view, OC acts similarly to that of aerosol sulfate, in that it scatters incoming sunlight and generally acts

to cool the Earth-atmosphere system by reflecting some portion of incoming sunlight back to space that would otherwise reach the surface.

Black carbon, by contrast, is a strong absorber of solar radiation; particles containing BC in the atmosphere both scatter and absorb solar radiation. Because BC-containing particles prevent radiation from reaching the Earth's surface, they act to cool the surface, but because they absorb radiation, they warm the atmosphere itself. Their heat-trapping ability depends on how they clump together and join with other substances to make larger particles. While the atmospheric warming effect of BC and its surface cooling are well established, the resulting climate forcing from BC has not been established clearly. This uncertainty arises for two basic reasons. First, BC emission inventories are uncertain, and therefore the actual amount of BC in the air is in question. Second, the manner in which BC is mixed with other aerosol material, such as sulfate and organics, is critical to its radiative impact. If the BC is mixed with other aerosol material, which is what most atmospheric measurements show, then its radiative warming effect is considerably enhanced over that of BC existing as separate particles. Previous work has shown that the overall radiative effect of aerosol BC depends significantly on the manner in which that BC is mixed with non-absorbing aerosols such as sulfate (Jacobson, 2000; Chung and Seinfeld, 2002).

Chung and Seinfeld, (2002) compared the predicted direct radiative of BC with those of previous studies. Many of the previous estimated BC radiative forcings are relatively small because they considered only fossil fuel BC and not biomass burning. In Figure 2, predicted BC radiative forcing is shown as a function of the global BC burden for the studies in which the global burdens can be determined. Even when differences in global burdens are taken into account, discrepancies among the different studies still exist. Another important factor affecting radiative forcing is the actual three-dimensional distribution of BC aerosols, which is different for fossil fuel and biomass burning BC. The geographical distribution is important because the radiative forcing is strongly dependent on the surface albedo, the presence of clouds, and the interaction of scattering and absorbing aerosols in the case of an internal mixture (Haywood et al., 1997; Haywood and Ramaswamy, 1998). Finally, uncertainties in the size distribution of the aerosols lead to variabilities in the predictions.



**Figure 2.** Comparison of BC radiative forcing predictions versus BC global burden by various authors (Chung and Seinfeld, 2000).

Black carbon inventories rely on different assumptions and on data related to emission activities, PM emission factors, and source profiles, all of which apportion PM mass to BC and other chemical constituents. These differences may be a major cause of discrepancies and uncertainties in model predictions. Bond et al. (1998) identifies PM mass emission factors and the BC fraction of emitted PM (i.e., "source profiles") as the most variable. Currie et al. (2002) show more than a factor of seven in the range of BC concentrations for different measurement methods commonly used throughout the world.

Global BC emission inventories are based on international fuel consumption estimates. Regional BC inventories have also been created. Bond et al. (2002) estimated that North American sources contribute 6% of global emissions (6.63 Tg BC/yr) (1 teragrams (Tg) =  $1 \times 10^9$  kilograms). Battye et al. (2002) ranked the major contributors to U.S. BC emissions as: 1) non-road diesel exhaust (21%); 2) on-road diesel exhaust (15%); 3) prescribed forest fires (7.9%); 4) open burning (7.7%); and 5) residential wood combustion (4.8%). Natural wildfires were not considered as manmade sources in Battye's analysis, although 100 years of fire suppression have caused them to be large emitters in recent years. Gasoline engine cold-starts and high emitters, which have been shown to contain substantial BC fractions (Zielinska et al., 1998), were not considered in this analysis.

Agricultural biomass burning and wildfire activity throughout the world are major sources of BC and other atmospheric aerosols that adversely affect global climate, health, and

visibility. The chemical characterization of particles from burning is essential for assessing its contribution in ambient air and, in turn, for predicting the health and environmental effects of prescribed and wildfire burning. Due to emission variation, sampling artifacts, and measurement method differences, fundamental challenges exist in determining the carbon composition of aerosols that accurately represent large-scale vegetative burning.

At present, there is no official BC emissions inventory at the national level. Current emissions models have the ability to estimate BC emissions based on the national emission inventory and default speciation profiles. However, U.S. EPA has recently formed a working group with a two-year schedule to compile improved speciation profiles. Eventually, these speciation profiles will be incorporated into emissions models, such as the Sparse Matrix Operator Kernel Emissions model (SMOKE) to improve BC emissions estimate.

In California, motor vehicles are a significant source of fine carbonaceous particle emissions. Professor Harely's team at UC Berkeley measured gas- and particle-phase pollutant concentrations in the Caldecott Tunnel in the San Francisco Bay Area during the summer of 1996. Fine particle BC and polycyclic aromatic hydrocarbons (PAH) concentrations were normalized to fuel consumption to compute emission factors. Light-duty vehicles emitted  $30 \pm 2$  mg of fine BC particle per kg of fuel burned (about 4.6 mg/mi). Dr. Norbeck of University of California, Riverside, tested PM emissions rates from 10 gasoline-fueled vehicles (MY 1979-1994). On vehicle average, elemental carbon emissions was reported about 1.92 mg/mi.

In 1996, a California Institute of Technology (Caltech) team quantified gas-and particle organic compounds present in the tailpipe emissions from an in-use fleet of gasoline-powered automobiles and light-duty trucks using two-stage dilution source sampling systems. Average elemental carbon emissions was reported at about 1.22 mg/mi. Professor Michael Kleeman of University of California, Davis, recently conducted PM source sampling of light-duty vehicles at the ARB's Haagen-Smit Laboratory in El Monte. Newer vehicles were tested (MY 1999-2002). Preliminary results from source testing of low emission vehicles indicate that PM emissions rates (about 1-3 mg/mi) were significantly lower than previously released data that did not include vehicles newer than model year 1995. A very crude estimate of elemental carbon emissions would be about 10 percent of total PM emissions or about 0.2 mg/mi.

As mentioned above, uncertainties in measurement methods contribute to the large uncertainty in the BC inventory. For the purposes of climate change emissions inventories, BC is defined as the carbon component of particulate matter that absorbs light. However, this specific component of particulate matter is difficult to measure. Methods that measure light absorption in particulate matter assume that BC is the only light absorbing component present; however, some components of OC may also absorb light; in this case, inventories of BC and OC may overlap. The various measurements of light-absorbing carbon are not well related, and consensus on interpretation has not yet been reached for the current suite of available measurement techniques. "Black" carbon

is defined optically, by measuring the change in light transmittance or reflection caused by particles. However, the attenuation of light by particles collected on a filter is usually enhanced over that of suspended particles and cannot be used without adjustment.

Most source-characterization studies do not measure BC, but rather so-called “elemental” carbon (EC) using thermal optical methods rather than absorption technique. This type of measurement is widely used in air-quality and source-characterization applications. Large numbers of OC and EC measurements have been reported by using thermal/optical methods. Results of method comparisons among many laboratories provide ambiguous results owing to subtle differences in the methods applied and the samples included in the comparison. There is a need to evaluate a treatment of the relationship between each measurement method and the quantity of interest—that is, light absorption.

In summary, understanding the role of aerosols in climate change requires inclusion of realistic representations of aerosols and their radiative forcings in climate models. Like greenhouse gases, light absorbing aerosols are anthropogenically produced during combustion of fossil, biomass, and bio fuels. However, compared to greenhouse gases with long atmospheric residence times, the optical properties and temporal and spatial patterns of aerosols are poorly known. Uncertainty in aerosol radiative forcing arises because neither emission factors, which determine atmospheric concentrations, nor optical properties are fully known.

The ARB is required under AB 1493 to adopt regulations that reduce greenhouse gas emissions from motor vehicles. However, particulate emissions are also believed to play a significant role in global warming. Furthermore, unlike the benefits associated with reductions in greenhouse gas emissions which take decades to fully realize, reductions in particulate matter emissions yield immediate improvements due to their short atmospheric lifetime, thus efforts to better characterize and subsequently control particulate matter can have an immediate and potentially profound impact on addressing global warming. However, due to the basic uncertainties regarding the actual impact of BC emissions on climate, it is impossible at this time to have confidence in any numerical prediction of the effect of BC emissions from light-duty motor vehicles. A need exists to systematically identify the net climatic effect of reducing emissions of fine particles, in particular carbonaceous aerosols. As more definite scientific evidence becomes available, the ARB could also consider the climate change impacts of these pollutants in its regulatory decisions.

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